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Mass balanced based LCA of a common carp-lettuce aquaponics system

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ABSTRACT

An aquaponics system (AS) is an integrated system that combines a recirculating aquaculture system and a hydroponics system (HS). It is designed to recover nutrients released from fish and transfer them to plants to provide a system more environmentally-friendly than the two systems working separately. As a result, several AS are under development, but little information is available about their overall performances. The aim of this study was to assess nutrient-use efficiency and environmental impacts of an AS, specifically a common carp-lettuce AS located in a greenhouse. Nutrient budgets of nitrogen (N) and phosphorus (P) were calculated and Life Cycle Assessment (LCA) was performed for the AS and for a lettuce Individual Hydroponics System (IHS), similar to the HS of the AS, operating in the greenhouse at the same time. The experiment was performed over a 52-day cycle, which corresponds to the growing time required to harvest marketable lettuce. The nutrient budgets were well balanced, with 24.6% of the N unaccounted-for, most likely due to N2 gas emission, and 6.6% of the P unaccounted-for, most likely due to having underestimated the quantity of sediment. At the beginning of the experiment, N represented 55.9%, 37.1% and 0.1% of the total N input in the formulated feed, stocked fish and lettuce seedlings, respectively. At the end of the experiment, N represented 47.6% and 0.4% of the total N input in the harvested fish and lettuce, respectively. At the beginning of the experiment, P represented 56.94%, 40.20% and 0.03% of the total P input in the formulated feed, stocked fish and lettuce seedlings, respectively. At the end of the experiment, P represented 51.52% and 0.42% of the total P input in the harvested fish and lettuce, respectively. LCA clearly indicated two environmental impact hotspots: the origin of nutrients and energy use. One kg of lettuce growth in the AS clearly had lower environmental impacts than that in the IHS for climate change, acidification, eutrophication, land competition and cumulative energy demand; however, a decrease in water dependence was not observed. The indicator for net primary production use highlighted the dependence of the AS on natural resources, especially fish meal and fish oil. Compared to the use of chemical nutrients in the IHS, the use of nutrients from formulated feed in the AS decreased climate change impact but increased the use of natural resources.

1. Introduction

Manure has long been used as a fertilizer in terrestrial agriculture and is a sustainable way to provide nutrients to crops. Similarly, aquaponics is an integrated aquaculture system in which fish farming and soilless culture are combined to recycle nutrients. Aquaponics systems (AS), in which edible plants recover dissolved nutrients released in the wastewater of fish culture, are considered a form of sustainable production (Graber and Junge, 2009). AS is historically set up in a recirculating aquaculture system (RAS) connected to a hydroponics system (HS), decreasing water use (Goddek et al., 2015; Klinger and Naylor, 2012; Love et al., 2014). The present study was performed within the French project APIVA (AquaPonie Innovation Végétale et Aquaculture) with the objective to (1) model the operations in AS to determine its production capacities and assess its effectiveness in treating fish waste; (2) provide technico-economic data to help stakeholders support and develop AS projects; (3) obtain data on quality (taste, nutritional values, microbiology, etc.) of plants produced in an AS; and (4) anticipate regulatory issues that may occur if AS is developed in Europe.

In a preliminary study on environmental impacts, Love et al. (2015) investigated the energy and water use of a small-scale raft AS, but did not relate it to nutrient release into the surrounding environment. To this end, several studies have calculated a nutrient budget to determine the fate of nitrogen (N) (Delaide et al., 2017; Endut et al., 2014; Fang et al., 2017; Wongkiew et al., 2017a; Zou et al., 2017), but rarely the

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fate of phosphorus (P) (Cerozi and Fitzsimmons, 2017; Delaide et al., 2017). The nutrient budget calculates the allocation of nutrients among the different compartments of the AS (fish, crop, water, sludge, gas emissions, unaccounted-for) (Cho and Kaushik, 1990) but requires analyzing each compartment to obtain an accurate budget. Unaccounted-for nutrients represented more than 30% of N in Fang et al. (2017), 20–40% of N in both Zou et al. (2017) and Wongkiew et al. (2017b) and more than 50% in Delaide et al. (2017). Unaccounted-for P represented more than 80% in Delaide et al. (2017) and 8–13% in Cerozi and Fitzsimmons (2017). Distribution of nutrients among plants, fish and other compartments of the AS in these studies were not compared because of their diversity (with or without sludge removal, fish feed distribution:crop area ratio, culture design, water renewal ratio, etc.). Instead, the NUE (Nitrogen Use Efficiency) indicator was developed (Fang et al., 2017; Hu et al., 2015; Zou et al., 2017). In AS, NUE is the percentage of total N inputs, mainly provided by fish feed, recovered in biomass. Hence, depending on the treatment, NUE was 40–47% in Fang et al. (2017), 34–41% in Hu et al. (2015) and 35–50% in Zou et al. (2017). Therefore, NUE is only a rough estimate of the system's ability to improve water quality by producing biomass, without further indication of other environmental impacts.

Life Cycle Assessment (LCA) is a methodological framework that estimates multiple indicators of environmental impact of a production system. Several LCA studies have been performed on RAS (Aubin et al., 2006; Ayer and Tyedmers, 2009; Badiola et al., 2017; Roque d'Orbcastel et al., 2009; Samuel-Fitwi et al., 2013; Wilfart et al., 2013), but to our knowledge, few have been published on AS (Boxman et al., 2017; Forchino et al., 2017; Hollmann et al., 2016; Xie and Rosentrater, 2015) given the diversity of existing AS. Most of these studies, however, examined tilapia AS (Boxman et al., 2017; Hollmann et al., 2016; Xie and Rosentrater, 2015). LCA has shown that energy and formulated feed contribute most to environmental impacts of AS, regardless of the approach used to address co-products: system expansion (Boxman et al., 2017), economic allocation (Hollmann et al., 2016; Xie and Rosentrater, 2015) or mass allocation (Forchino et al., 2017).

While most studies on AS have combined a variety of vegetables (tomato, basil, lettuce, cucumber, pak choi, etc.) with tilapia (*Oreochromis* sp.), only a few studies have included carp (*Cyprinus carpio*) (Hussain et al., 2015; Naegel, 1977; Shete et al., 2016), which is one of the most widely reared fish species in the world. In addition, only a few studies have analyzed P and the P budget, and to our knowledge, no study has combined a nutrient budget with LCA. Thus, the aim of this study was to assess, at a commercial scale, relative advantages of AS, specifically those of producing lettuce in an AS compared to doing so in an HS, by calculating nutrient budgets of total N (TN) and total phosphorus (TP) and performing an LCA.

2. Materials and methods

The experiment was conducted from 26 January to 18 March 2016 inside a single greenhouse at the RATHO (Rhône-Alpes Techniques Horticoles, Brindas, France) facilities. The greenhouse (total area = 225 m^2) contained two systems (Fig. 1): (1) the AS (60 m^2) and (2) a separate, individual HS (IHS) (20 m^2) used as a control, similar to that in the AS. The remaining area was corridors.

2.1. Aquaponics system

The AS consisted of a RAS for fish rearing that was connected to a HS for crop cultivation. In the RAS, water was continuously run through the entire system at a flow rate of 45 $m^3 h^{-1}$. Addition of potassium bicarbonate (219 g day^{-1}, on average) maintained the water pH between 6.5 and 7.2. The added potassium (K) also benefitted the plants because it is one of the elements that most limits plant growth. No other chemicals were added to the system during the experiment. A rotary drum filter with a 60 µm mesh was placed after the merged outflow of four 3.7 m^3 fish rearing tanks. The rotary drum filter removed solid particles from the water into a settling tank and concentrated them into sludge. The sludge was transferred from the settling tank three times a week into a second tank that contained a flocculating agent (Superfloc from Kemira© at 80 ml l00 l^{-1} of sediment). The sediment was then transferred into a water-permeable geotextile bag, which was stored and passively dried. At the exit of the drum filter, filtered water entered a common tank in which makeup water was added continuously at the rate of 200 l of tap water kg^{-1} of feed day^{-1} (corresponding to a 6% water exchange rate). From this common tank, water was distributed between the HS, the RAS and the discharge wastewater (whose volume equaled the makeup water minus evaporation). In the RAS, water was pumped from the common tank through a UV filter before being transferred into a moving bed biofilm reactor (MBBR), after which it was returned to the rearing tanks. An air blower provided high oxygenation capacity inside the MBBR, facilitating the constant movement of the media and delivering oxygen-saturated water to the rearing tanks. The specific surface area of the media was 850 $m^2 m^{-3}$. In the AS's plant compartment, four culture areas of 4.8 m^2 each were each composed of a bed raft (550 l) covered by floating rafts (extruded polystyrene foam) with a density of 16 seedlings m^{-2}. Water was continuously run through the bed raft (under the floating rafts) at a flow rate of 4 $m^3 h^{-1}$ (1 $m^3 h^{-1}$ per bed raft, corresponding to 1.8 renewals per hour in each bed raft), and after providing sufficient oxygen, was returned to the common tank.

Common carp was chosen as the reared fish for its robustness and frequent use in the region. Fish density was maximized according to the size of the biofilter and the volume of the tanks. A total of 1 001 fish (mean weight = 647 g ± 140.9 g, n = 1 001) were randomly and equally stocked in the four rearing tanks. The fish were manually fed a commercial carp feed ("Carpe Extrude", Le Gouessant©, 32% crude protein, 9% crude fat and 1% P), and diets were determined according to fish weight and water temperature. A mean diet of 1.1 kg feed 100 kg^{-1} of fish biomass was distributed during the experiment. Lettuce (equal proportions of oak leaf and Batavia varieties) was chosen because it is easily cultivated in HS and for its ability to grow well under the experiment's winter photoperiod. The temperature of the greenhouse was monitored continuously and recorded every 5 min (Hoogendoorn probe). Lettuce plants were established at the four-leaf stage at the beginning of the experiment, and all the seedlings used were bought at the same time at the same place.

2.2. Individual hydroponics system

The IHS was designed as the control for the HS in the AS. In the IHS, nutrients were supplied via nutritive solutions (Table 1) to each raft bed. Since water was static under the rafts, small bubblers were connected to the biofilter's air blower to provide enough oxygen in the nutritive solution of each raft bed. The nutritive solution was automatically prepared and distributed once a week by a device (running Angela 2.0 software, ICL Specialty Fertilizers, Geldermalsen, The Netherlands) that measured water conductivity and composition. The nutritive solution was renewed weekly by releasing 20% of the used solution. To the remaining 80%, hydroponic stock solution and tap water were added until the expected volume (550 l per raft bed), conductivity (1 500 µS cm^{-1}) and water composition (TN = 120 mg l^{-1}, TP = 25 mg l^{-1}) were reached.

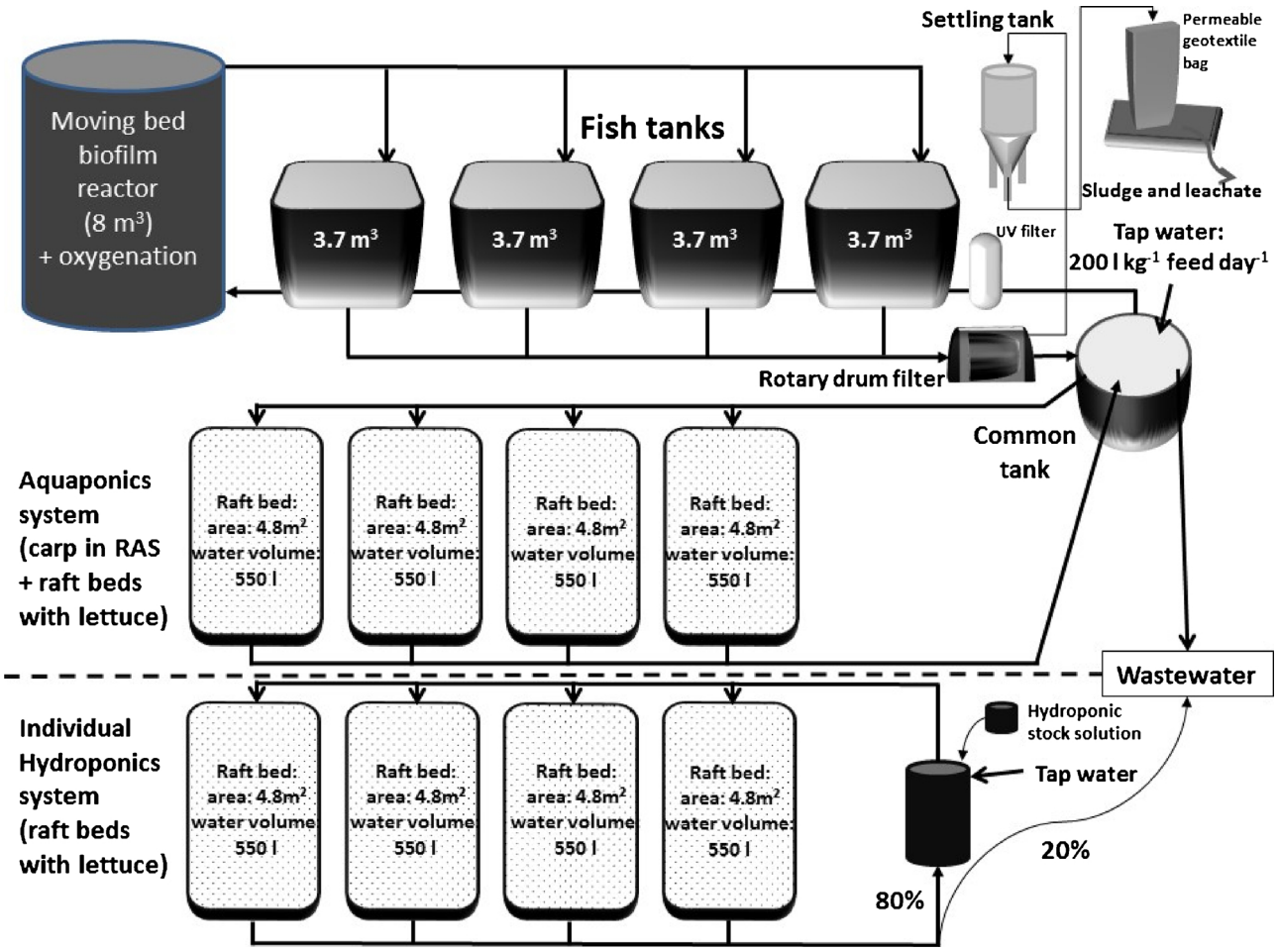
Settling tank
Permeable geotextile bag
Sludge and leachate
Moving bed biofilm reactor (8 m³) + oxygenation
Fish tanks
3.7 m³
3.7 m³
3.7 m³
3.7 m³
UV filter
Tap water: 200 l kg⁻¹ feed day⁻¹
Rotary drum filter
Common tank
Aquaponics system (carp in RAS + raft beds with lettuce)
Raft bed: area: 4.8m² water volume: 550 l
Raft bed: area: 4.8m² water volume: 550 l
Raft bed: area: 4.8m² water volume 550 l
Raft bed: area: 4.8m² water volume: 550 l
Wastewater
Individual Hydroponics system (raft beds with lettuce)
Raft bed: area: 4.8m² water volume 550 l
Raft bed: area: 4.8m² water volume 550 l
Raft bed: area: 4.8m² water volume 550 l
Raft bed: area: 4.8m² water volume: 550 l
Hydroponic stock solution
Tap water
20%
80%

Fig. 1. Diagram of the aquaponics and individual hydroponics systems used. In the latter, the nutritive solution was renewed weekly by releasing 20% of the used solution. To the remaining 80%, hydroponic stock solution and tap water were added until the expected volume (550 l per raft bed), conductivity (1 500 µS cm-1) and water composition (TN = 120 mg l-1, TP = 25 mg l 1) were reached. RAS = recirculating aquaculture system.

Table 1
Quantities of fertilizer compounds added and mixed in a 200 l tank to make the nutritive solution to grow lettuce under hydroponic conditions during three physiological stages. Nutritive solutions were automatically prepared using Angela 2.0 software.

Fertilizer compound	Physiological stage		
	"Beginning" phase (for 1 week)	"Shoot" phase (for 2 weeks)	"Production" phase (until the end of the production cycle)
Nitric acid 53.5% (l)	6	6	6
Ammonium nitrate (kg)	3	4	3
Monopotassium phosphate (kg)	5	2	2
Potassium sulfate (kg)	0	5	10
Magnesium sulfate (kg)	4	4	4
Microelements, *"OligoVeg"* (g)	400	400	400
EDTA-Iron *"Ferveg" (g)*	800	800	800

2.3. Monitoring and measurements

2.3.1. Fish and feed

The amount of feed distributed and its dry matter (DM, 24 h at 60 °C), TN and TP contents were measured. TN content was measured using an elemental analyzer (vario PYRO cube, Elementar, Langenselbold, Germany). TP content was measured using the molybdate blue/ascorbic acid method at 820 nm after mineralization and acid digestion (AFNOR, 1992).

For fish, TN content was measured in dorsal muscle from 10 fish randomly harvested at the end of the experiment from the four fish tanks using the same analytical method as for feed. TP content was determined from data available for carp in the literature (Schreckenbach et al., 2001) giving a TP content of 0.48 ± 0.09% fresh weight for a dry matter of 26.78 ± 4.12%. Both TN and TP contents in carp were assumed to be the same at the beginning and end of the experiment. Each fish was weighed at the beginning and end of the experiment. In addition, every two weeks a subsample of 100 fish were weighed to determine intermediate total fish biomass. No fish mortality was observed. The feed conversion ratio (FCR) was calculated as follows:

$$FCR\ (kg\ kg^{-1}) = \frac{food\ \ distributed\ \ (kg\ DM)}{fish\ \ weight\ \ gain\ \ (kg)}$$

2.3.2. Lettuce

At the beginning and end of the experiment, proximal compositions of TN and TP were measured using the same methods as for feed. At the

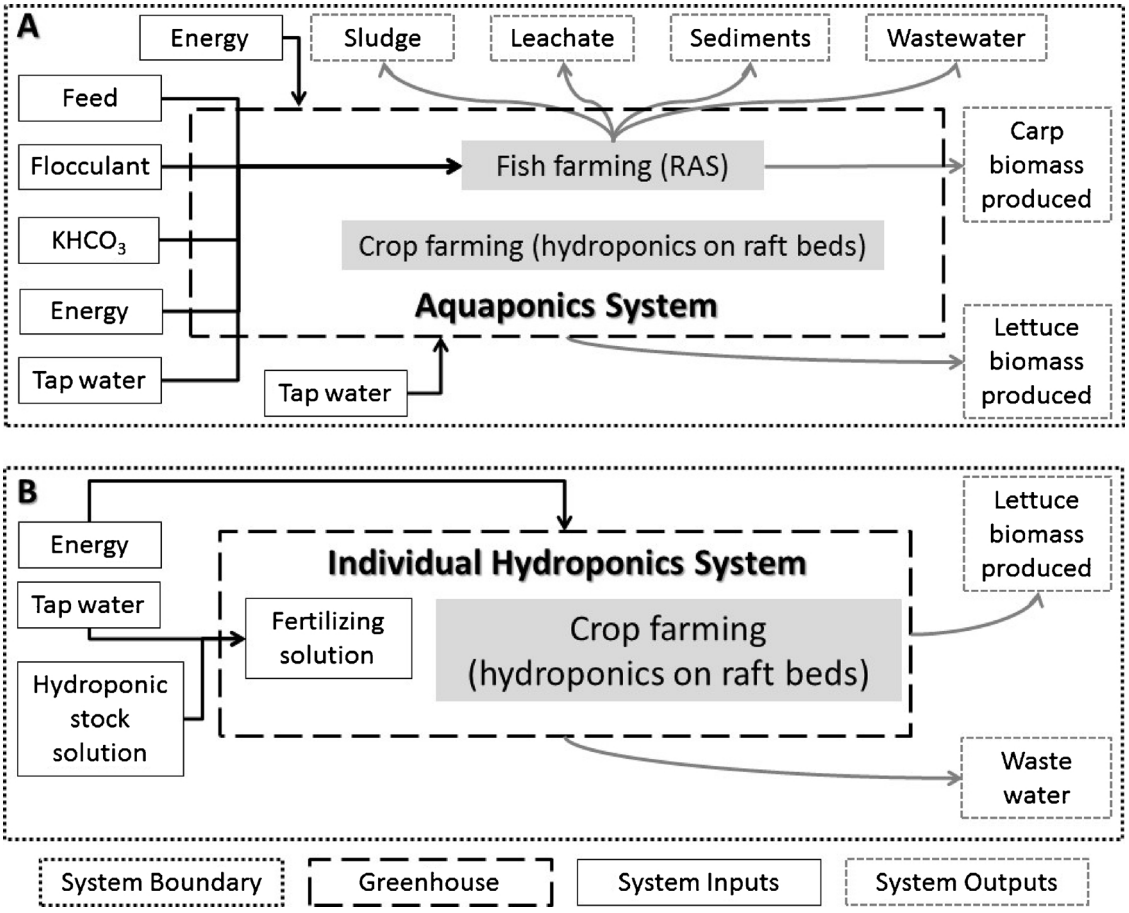

Fig. 2. Flow chart of aquaponics (A) and individual hydroponics (B) systems for Life Cycle Assessment. $KHCO_3$ = potassium bicarbonate.

beginning and end of the experiment, DM was determined (24 h at 60 °C) from three random samples of potting soil used for seedlings and ten random samples of seedlings and entire lettuce plants (roots + leaves). Dead leaves and all other crop biomass were collected and weighed, and their DM was measured during the experiment.

2.3.3. Water

Temperature, dissolved oxygen concentration and pH were continuously monitored and recorded every 5 min (Hoogendoorn probe). Conductivity was recorded once a day (Odeon multiparameter probe). All of these measurements were performed in the common tank of the AS (Fig. 1). A water meter recorded the total volume of makeup water input from the network throughout the entire experiment; wastewater volume was assumed to equal the amount of water input. To calculate the mass balance and determine the amounts of N and P in the systems, a water sample was collected at the beginning and end of the experiment directly from water in the common tank of the AS and from the discharge wastewater of the IHS. TN and TP contents were measured for each sample by spectrophotometry (NF EN 25663 and NF EN ISO 6878, respectively). Since wastewater was released from the common tank, TN and TP contents in the outlet water of the AS were assumed to remain constant throughout the experiment and equal those from analyses performed at the end of the experiment from water sampled in the common tank. The makeup water was sampled once to measure inlet TN and TP contents, which were assumed to remain constant throughout the experiment.

2.3.4. Sediment

No sediment was present in the AS at the beginning of the experiment. Since the flocculant agent used to remove particulate organic matter did not contain N or P compounds and was added in small amounts, it was ignored in the mass balance calculation. Leachate collected in the geotextile fabric bag was stored in a closed tank, and its total volume was measured. Mean TN (NF EN 25663 and NF ISO 15923-1) and TP (NF EN ISO 6878) contents in the leachate were analyzed. At the end of the experiment, the total weight of sediment and mean TN (NF EN 25663 and NF ISO 15923-1) and TP (NF EN ISO 6878) contents were measured from samples collected in the upper, middle and lower layers of the bag. The water in the settlement tank was not drained at the end of the experiment, and no samples were taken from it. To estimate the nutrients it contained, we assumed that its TN and TP concentrations were similar to those measured in the leachate. At the end of the study, the amount of sediment settled on the bottom of the AS raft beds was also estimated by first turning off the pump (to stop water flow under the rafts) and measuring suspended matter concentration in the water. The entire volume of water and sediment contained in one raft bed were then mixed, and the suspended matter concentration in the water was measured again. Thus, the amount of settled sediment was determined as the difference between the two concentrations, multiplied by the volume of water in the raft bed. The operation was performed twice to obtain a representative value. TN and TP contents in the settled sediment were assumed to be the same as those of the sediment stored in the geotextile bag.

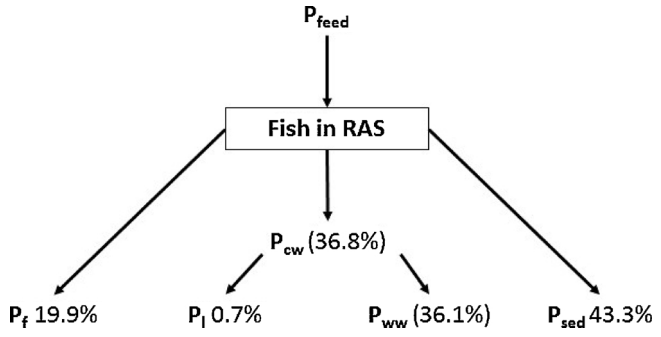

Fig. 3. Distribution of phosphorus, expressed as a percentage of the phosphorus in the feed (P_{feed}), biomass of fish produced (P_f), circulating water (P_{cw}), biomass of lettuce produced (P_l), wastewater released (P_{ww}), and sediment and leachate released (P_{sed}). Percentages were measured except for those in parentheses, which were estimated. RAS: recirculating aquaculture system.

2.4. Statistical analyses

A Wilcoxon test was used to compare lettuce growth performances in the two systems (IHS vs. AS) at three weighing dates (days 0, 28 and 52). A non-parametric test was used because data did not meet the assumption of normality and/or homoscedasticity (previously tested with Shapiro and Bartlett tests, respectively). Statistical analyses were performed using R software (version 3.4.4).

2.5. Nutrient budget

Nutrient inputs and outputs were used to calculate mass balances of N and P compounds. TN and TP contents in feed, fish, lettuce, water and sediment were obtained as previously described. For AS, the mass balance was calculated for each nutrient (N or P) as its amounts (g) in system components:

$$nutrient \quad budget = (F + Pb + Bb + Wb + Wf) - (Be + Pe + We + Ww + S + L)$$

where:

F is feed distributed

Pb and *Pe* are seedlings + potting soil at the beginning and end of the experiment, respectively, including dead leaves and all other crop biomass

Bb and *Be* are fish biomass at the beginning and end of the experiment, respectively

Wb and *We* are water at the beginning and end of the experiment, respectively

Wf and *Ww* are input water and wastewater, respectively

S is sediment at the end of the experiment

L is leachate at the end of the experiment

2.6. Life cycle assessment

LCA is a standardized method (ISO 14040 and 14044) used to estimate environmental impacts of a product or a service throughout its life-cycle stages, from “the cradle to the grave”. LCA follows four main phases: (1) describe the goal and scope of the study and the system (define the context of the study, identify a function of the product, determine a functional unit and set system boundaries), (2) perform a Life Cycle Inventory (identify and quantify the system’s inputs and outputs related to the function studied), (3) assess environmental impacts and (4) interpret results.

In this study, LCA was performed from the cradle to the farm gate (Fig. 2) for a 52-day cycle, corresponding to the time needed to grow marketable lettuce. The impact indicators considered were acidification, eutrophication, climate change, total cumulative energy demand, net primary production use, water dependence and land competition. Acidification (AC, kg SO_2-equivalents) refers to negative effects on soils, ground and surface water, and ecosystems from acidifying pollutants. It was calculated using average European acidification potential factors from Huijbregts (1999). Eutrophication (EU, kg PO_4-equivalents) refers to potential impacts of high levels of nutrients, especially N and P, in the environment. It was calculated using factors developed by Guinee et al. (2002) and adding the theoretical oxygen demand caused by solid waste from fish farms. Climate change is the potential impact of gas emissions on heat-radiation absorption in the atmosphere. It was calculated according to 100-year-horizon global warming potentials (GWP100, kg CO_2-equivalents) of the International Panel on Climate Change (Houghton et al., 1996). Land Competition (LC, m^2year) refers to human use of land that delays natural restoration of land quality during the period of occupation (Guinee et al., 2002). Total cumulative energy demand (CED, MJ) refers to the consumption of all energy sources used. Net Primary Production Use (NPPU, kg carbon) refers to the amount of net primary production (biomass produced by photosynthesis) required as a biotic resource input that cannot be used for other purposes. It was calculated according to Papatryphon et al. (2004). Water dependence (WD, m^3) (Aubin and van der Werf, 2009) equals the water used by the system.

Since common carp and lettuce are produced in the same system, resource use and emissions can be allocated to the two co-products based on their economic values, as presented and discussed in aquaculture LCA studies (Ayer et al., 2007; Hollmann et al., 2016). The resulting impacts, however, depend greatly on commodity prices and can therefore vary over time. Furthermore, after a 52-day cycle, lettuce reaches its highest price, but carp does not. Thus, to avoid allocation we chose to apply system expansion (Weidema and Schmidt, 2010). Since the aim of the study was to assess the efficiency with which an AS used nutrients released from fish farming to produce lettuce, the only functional unit considered was 1 kg of lettuce growth after 52 days. Fish feed was the only source of nutrients for carp growth in the RAS. Consequently, the nutrients not recovered in fish biomass were assumed to be the only ones available for lettuce, even though small percentages of total amounts were actually present in circulating water at the beginning of the experiment and in the makeup water. By extension, fish feed was considered the only source of nutrients for fish and lettuce. Since P is a conservative element, the environmental impacts from producing carp biomass that were allocated to the production of 1 kg of lettuce were calculated according to the following proportion (AllocLettuce):

$$AllocLettuce = \frac{Pl}{Pl + Pf}$$

where *Pl* is the percentage of P from fish feed recovered in lettuce and, *Pf* is the percentage of P from fish feed recovered in fish (Fig. 3).

To assess relative advantages of producing lettuce in an AS, environmental impacts of producing lettuce in the AS were compared to those of producing lettuce in the IHS. Emissions and impacts were calculated using SimaPro® software v8.3.0.0 (PRé Consultants, Amersfoort, The Netherlands), using the attributional databases ecoinvent® v3 and EcoAlim AGBv1.3 (Wilfart et al., 2016) for background data (Tables A1 and A2).

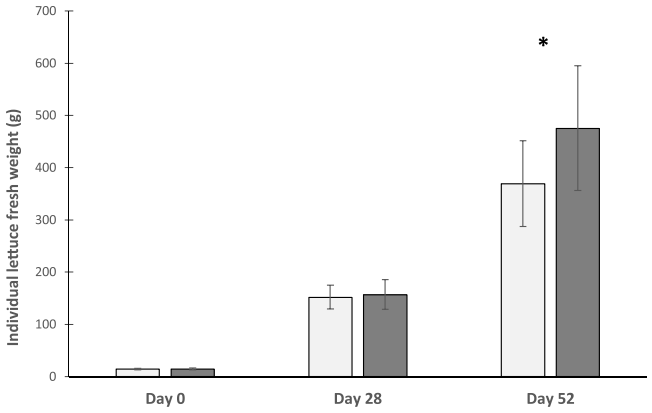

Fig. 4. Mean fresh weight of individual lettuce plants in the aquaponics system (light gray bars) and individual hydroponics system (dark gray bars) at each stage (days 0, 28 and 52) during the 52-day experiment. The asterisk indicates a significant difference between means of the two systems (Wilcoxon test, $p < 0.001$). Error bars equal ± 1 standard deviation.

3. Results and discussion

3.1. Carp production

During the experiment, water had mean (± 1 standard deviation) temperature of 15.5 ± 0.9 °C, dissolved oxygen concentration of 7.81 ± 1.25 mg l^{-1}, pH of 6.76 ± 0.21 and conductivity of 1197 ± 42 mS cm^{-1}. It is worth noting that the optimal temperature for carp growth, 20–30 °C (Billard, 1995), is higher than the mean temperature recorded. At the beginning of the experiment, total weight of fish in the system was 648 kg, yielding a density of 43.8 kg m^{-3}. At the end of the 52-day experiment, total fish weight was 829 kg (total weight gain of 181 kg), yielding a final density of 56.0 kg.m^{-3} (n = 1 001). With 412 kg of feed (32% crude protein) distributed during the experiment, the FCR (2.26 kg feed kg^{-1} fish weight gain) was slightly higher than that commonly obtained in carp production (Fry et al., 2018), probably due to distributing more feed than the fish required, since a true test of satiety was not performed, and the study period was much shorter than the fish production cycle with a suboptimal water temperature.

Table 2
Quantities of nitrogen and phosphorus in inputs and outputs in each compartment of the aquaponics system, used to calculate the mass balances of nitrogen and phosphorus.

	Nutrient (g)	
Compartment	Nitrogen	Phosphorus
Inputs		
Feed	25 047	4 403
Stocked fish	16 613	3 108
Circulating water at the beginning	2 592	213
Inlet water	496	5
Lettuce seedlings	21	2
Outputs		
Harvested fish	21 292	3 984
Outlet water	7 549	975
Circulating water at the end	2 427	324
Sediment	2 076	1 741
Harvested lettuce	174	32
Leachate	254	166
Unaccounted-for: Input — Output	10 997	509

3.2. Lettuce production

A marketable weight of lettuce was reached after a production cycle of 52 days, which is relatively long for lettuce, but not surprising, since the greenhouse temperature (14.6 ± 3.2 °C) and light intensity are relatively low in winter. In comparison, during spring and summer the production cycle in the same greenhouse usually lasts 32–35 days (personal data). During the production cycle, a total of 90.74 kg of lettuce biomass and 6.03 kg of dead leaves were harvested in the AS, while a total of 111.73 kg of lettuce biomass and 6.47 kg of dead leaves were harvested in the IHS. The dead leaves, collected throughout the production cycle, were caused mainly by a powdery mildew infection, which was attributed to the high humidity (> 75%) in the greenhouse in winter, when cold temperatures make ventilation difficult. The infection killed relatively few leaves since it occurred at the end of the cycle. Thus, lettuce growth was 23% higher in the IHS than in the AS.

Mean plant weight did not differ significantly between AS and IHS at the beginning (day 0) or middle of the experiment (day 28) but, was significantly lower in AS than in IHS at the end of the experiment (day 52). Thus, lettuce grew less in AS than in IHS during the second half of the experiment (Fig. 4). Light chlorosis was observed on the leaves in AS, which could explain the difference in growth. We decided not to provide plant-growth supplements to the AS, even though iron deficiency is known to cause light chlorosis (Rakocy et al., 2006), because we did not want them to interfere with the fertilizing potential of fish waste.

3.3. Nutrient budget

Formulated feed (25.0 kg N) and stocked fish (16.6 kg N) (Table 2) were the largest N inputs, representing 93.0% of the TN input (Fig. 5). A total of 22.1% of the TN input was released from the AS, mainly through outlet water (16.9%), followed by sediment (4.6%) and leachate (0.6%). The N budget was unbalanced, with 24.5% of the TN input unaccounted-for. Harvested fish (21.3 kg N) and harvested lettuce (174 g N) represented 48.0% of the TN input. The N retained in fish biomass growth represented 18.7% of N in the formulated feed distributed, which is less than the mean of 25% from results in Piedrahita (2003). The N retained in fish and lettuce biomass growth represented 19.3% of N in the formulated feed distributed, which is low compared to the NUE from previous studies, (Fang et al., 2017; Hu et al., 2015; Zou et al., 2017) (Table 3). Approximately 25% of total N input was unaccounted-for in our system. This agrees with results of previous studies and was due to gas emissions (Endut et al., 2014; Ru et al., 2017). N_2 was likely the main gas emission due to passive denitrification (an anaerobic process) and anoxic microsites present in the system (Endut et al., 2014), while ammonia emissions likely represented less than 0.25% of the unaccounted-for N (Thoman et al., 2001). Nitrous oxide from bacterial nitrification and denitrification (Zou et al., 2017) was also emitted from AS at a potential rate of 1.5–1.9% of N input (Wongkiew et al., 2017a).

Formulated feed (4.4 kg P) and stocked fish (3.1 kg P, Table 2) were the largest P inputs, representing 97.1% of the TP input (Fig. 6). A total of 37.3% of the TP input was released from the AS, mainly through sediment (22.5%), followed by outlet water (12.6%) and leachate (2.2%). The P budget was unbalanced, with 6.6% of the TP input unaccounted-for. Harvested fish (4.0 kg P) and harvested lettuce (32 g P) represented 51.9% of the TP input. The P retained in fish biomass growth represented 19.9% of P in the formulated feed distributed, which is less than the mean of 29% from results in Piedrahita (2003) and 42% for Cerozi and Fitzsimmons (2017). The P retained in fish and lettuce biomass growth represented only 20.6% of TP in the formulated feed distributed, while 71.7% of the P from formulated feed was recovered in plant (lettuce) and fish (tilapia) biomass growth (29.4% and

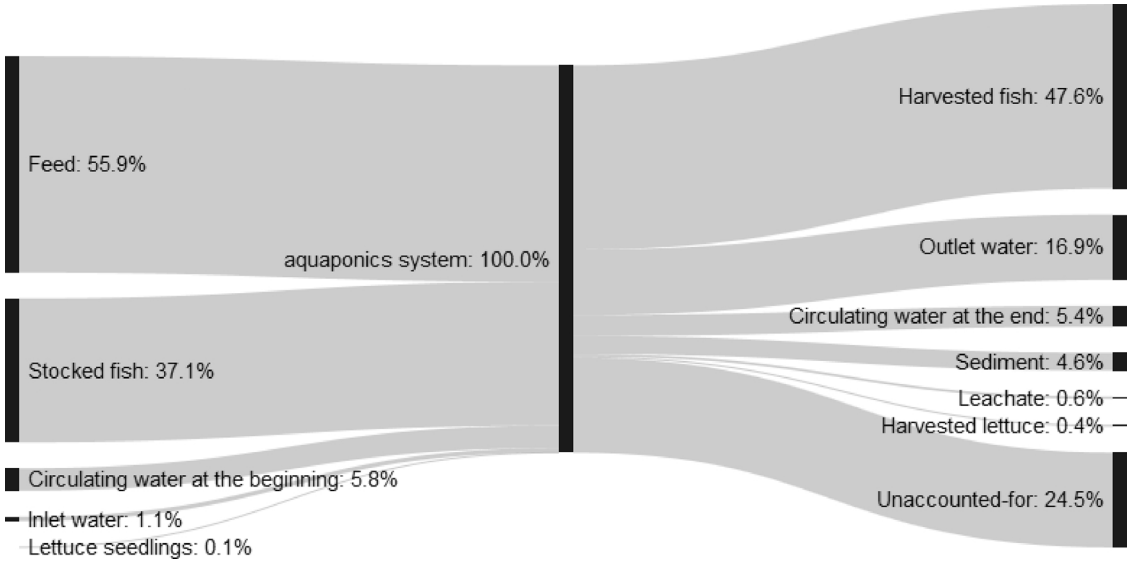

Fig. 5. Nitrogen budget in the aquaponics system. Values are percentages of the total nitrogen input to the system.

Table 3
Fate of nitrogen and phosphorus from feed in aquaponics system studies.

Fish species	Plant species	N from feed retained in(%)			P from feed retained in (%)			P in feed deposited in sediments (%)	Reference
		Fish	Plant	Plant + fish	Fish	Plant	Plant + fish		
Common carp	Lettuce	18.7	0.6	19.3	19.9	0.7	20.6	39.5	Present study
Common carp	Pak choi	22.6	–	43.8	–	–	–		Fang et al. (2017)
Common carp	Pak choi	–	–	35.2-50.0	–	–	–		Zou et al. (2017)
Nile tilapia	Lettuce	–	–	–	42.3	29.4	71.7	10.7	Cerozi and Fitzimmons (2017)
Nile tilapia	Lettuce and basil	–	–	–	–	–	10.0	5.0	Delaide et al. (2017)
Nile tilapia	Tomato	24.3	17.0	–	–	–	–	–	Hu et al. (2015)
Nile tilapia	Pak choi	19.4	15.0	–	–	–	–		Hu et al. (2015)
Atlantic salmon	–	36.5-47.1	–	–	20.4-38.6	–	–	–	Sun et al. (2016)
Several species	–	25.0[1]	–	–	29.0[1]	–	–	–	Piedrahita (2003)

[1] mean values calculated from Atlantic salmon, carp, channel catfish, sea bass, sea bream, rainbow trout and hybrid tilapia estimates.

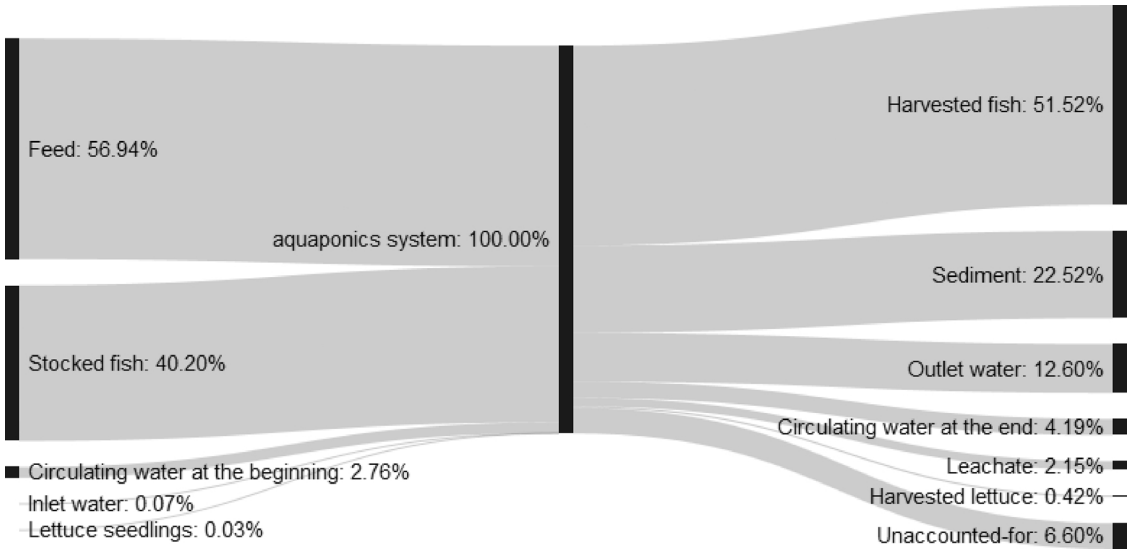

Fig. 6. Phosphorus budget in the aquaponics system. Values are percentages of the total phosphorus input to the system.

42.3%, respectively) by Cerozi and Fitzsimmons (2017). In their study, however, juvenile tilapia (20 g) were used, while larger fish were reared in our experiment. The rotary drum filter in our system removed most of the particulate matter, corresponding to 39.5% of the P from formulated feed distributed, while only 10.7% of P from formulated feed distributed was removed in the form of suspended solids or sludge in the system of Cerozi and Fitzsimmons (2017). Delaide et al. (2017) found less than 10% of the P from formulated feed recovered in plants and fish, and less than 5% in sludge. In this last study, nearly 90% of nutrients unaccounted-for in the budget were assumed to result from water spillage and inaccurate measurement, even with a low daily water exchange rate of 3.6% (Table 3).

Since P is a conservative element and analysis was performed for each compartment of the system, a well-balanced nutrient budget was expected. However, 6.6% of total P input was unaccounted-for, which is lower than the 11% observed by Cerozi and Fitzsimmons (2017). Some of this lack of balance, as well as for the N budget, was most likely due to inaccurate measurement and sampling, particularly of outlet water, along with underestimating quantities of sediment, especially in the settling tank.

The mean daily ration throughout the experiment was 7 923 g day^{-1} for 19.48 m^2 of crop area, corresponding to 419 g feed m^{-2} day^{-1}. Considering the plants' low N and P uptake, it seems necessary to redesign the AS to maximize its bioremediation potential by optimizing the plant:fish ratio. Lettuce uptake from circulating water was approximately 0.16 g N m^{-2} day^{-1} and 0.03 g P m^{-2} day^{-1} during the 52-day experiment. For comparison, Graber and Junge (2009) reported uptakes of 0.29 g N m^{-2} day^{-1} and 0.02 g P m^{-2} day^{-1} for eggplant; 0.43 g N m^{-2} day^{-1} and 0.07 g P m^{-2} day^{-1} for tomato; and 0.08 g N m^{-2} day^{-1} and 0.02 g P m^{-2} day^{-1} for cucumber, but only fruits were considered, not the entire plant.

To our knowledge, no literature data are available that express nutrient uptake m^{-2} day^{-1} for lettuce. According to the mass balance (Table 2), the sum of nutrients released from the fish farming compartment equaled 7 549 g and 975 g of "available" N and P, respectively. This indicates that it may be necessary to grow 833 and 585 m^2 of lettuce in the AS to take up the total dissolved N and P, respectively, from the circulating water. Assuming that P is the limiting nutrient, decreasing the amount of fish feed distributed from 419 to 15 g of fish feed m^{-2} of plant area per day would have met lettuce requirements, thus maximizing phytoremediation. This amount is less than the 60–100 g of fish feed m^{-2} of plant area per day reported in the literature (Rakocy et al., 2006) but within the lower range of the 15–42 g of fish feed m^{-2} of plant area per day observed by Endut et al. (2010).

This calculation assumes that lettuce can take nutrients up from water until they reach low concentrations. As nutrient concentrations decrease, conductivity decreases as well, theoretically decreasing plants' ability to absorb nutrients. It also assumes that the other macro- and micro-elements (e.g. K, Fe, Mg, Ca, S) are not limiting. For instance, K is considered one of the most limiting elements in aquaponics (Graber and Junge, 2009) but is usually added to AS as potassium bicarbonate or potassium sulfate to buffer the pH, as in this experiment.

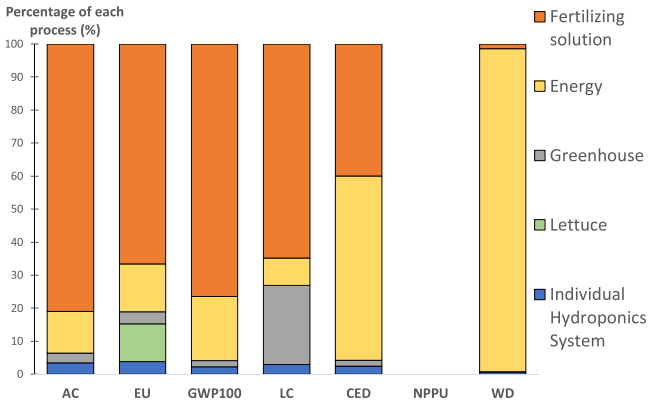

Fig. 7. Contribution of each process to the seven environmental impacts considered per 1 kg of lettuce growth after 52 days in the individual hydroponics system (AC: acidification, EU: eutrophication, GWP100: climate change, LC: land competition, CED: total cumulative energy demand, NPPU: net primary production use, WD: water dependence).

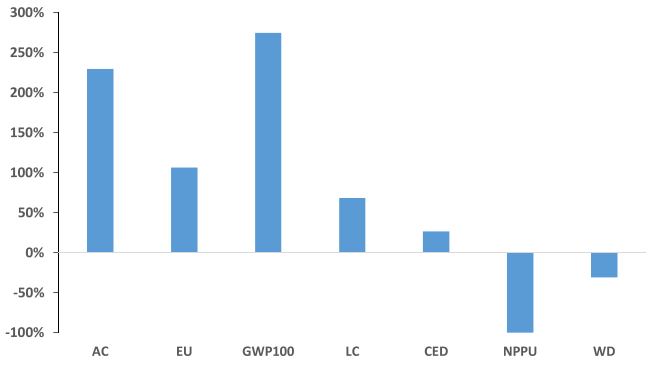

Fig. 8. Percentage difference of impacts per 1 kg of lettuce growth after 52 days of the individual hydroponics system relative to those of the aquaponics system, in each category: Acidification (AC), Eutrophication (EU), GWP100 (climate change), Land Competition (LC), Cumulative Energy Demand (CED), Net Primary Production Use (NPPU) and Water Dependence (WD).

Neori et al. (2007) reported that fish do not retain a large percentage of feed-borne P, which is mainly excreted and adsorbed by organic particles that are subsequently filtered and removed from the system. It is then often stored as dehydrated sludge or directly spread in its liquid form onto agricultural fields. This is confirmed by the mass balance performed, since 19.9% of the P provided by feed was fixed in fish biomass, only 0.7% was fixed by plant biomass and 39.5% was trapped in solid waste (sludge and sediment). Goddek et al. (2015) mentioned

Table 4
Environmental impacts of 1 kg lettuce growth after 52 days in the aquaponics system (AC: acidification, EU: eutrophication, GWP100: climate change, LC: land competition, CED: total cumulative energy demand, NPPU: net primary production use, WD: water dependence).

Impact category	Unit	Lettuce	Carp biomass produced[1]	Greenhouse	Crop farming	Water	Energy	Total
AC	kg SO_2 eq	0.000	0.004	0.004	0.004	0.000	0.018	0.030
EU	kg PO_4^{---} eq	0.000	0.006	0.001	0.001	0.000	0.004	0.012
GWP100	kg CO_2 eq	0.000	0.730	0.556	0.655	0.009	4.524	6.474
LC	m^2a	0.000	0.107	0.181	0.022	0.001	0.056	0.367
CED	MJ	0.000	42.150	7.322	10.508	0.164	215.351	275.495
NPPU	kg C	0.000	1.365	0.000	0.000	0.000	0.000	1.365
WD	m^3	0.000	0.028	0.000	0.001	0.000	0.135	0.164

[1] values represent only the impacts of carp production allocated to lettuce production (based on relative retention of P from feed).

that in RAS, 30–65% of P added via feed was filtered out of the system. The remaining P was discharged in overflow water and leachates or was retained in the RAS circulating water in its dissolved form (12 mg $l^{-1}$of $P\text{-}PO_4^{3-}$ for 12 mg l^{-1} of total P measured in the overflow water).

We demonstrated that P was a limiting element in AS when the feed:plant ratio decreased. Thus, optimizing P recovery in the AS is of interest. P recovery could be optimized by (1) mineralizing the fish sludge before returning the supernatant to the AS and (2) maximizing the crop area, thereby optimizing the fish:plant ratio. With the aim of rendering organic residues "trapped" in sludge soluble, sludge can be mineralized through aerobic or anaerobic biodigestion (Goddek et al., 2016b). Monsees et al. (2017) showed that aerobic treatment was the most effective for mineralizing P into orthophosphate ions, while both treatments had similar potential for K release. Monsees et al. (2017) also showed that concentrations of soluble P in the supernatant of aerobically treated sludge were three times as high (from 9.4 ± 0.7 to 29.7 ± 2.1 mg l^{-1}). Goddek et al. (2016a), however, observed greater plant growth when anaerobic biodigester supernatant was added to irrigation water, probably due to the acidifying action of ammonia (produced under anaerobic conditions from NO_3-) on the plants' rhizosphere. This occurred under alkaline conditions (pH = 8.1–8.7), in which plants tend to use ammonia as an N source (Goddek et al., 2016b).

3.4. Life cycle assessment

Contribution analysis of the production of 1 kg of lettuce growth after 52 days in the AS showed variable contributions of production stages to environmental impacts (Table 4). Since 0.7% and 19.9% of P from feed was recovered in lettuce and fish, respectively, AllocLettuce was 0.03. Energy use was the main contributor to WD (83%), CED (78%), GWP100 (70%) and AC (60%). The carp biomass produced was the main contributor to NPPU (100%) and EU (49%).

In the contribution analysis of the production of 1 kg of lettuce growth after 52 days in the IHS (Fig. 7), energy use contributed most to WD (98%) and CED (56%). For the remaining environmental impacts, the fertilizing solution contributed most to AC (81%), GWP100 (76%), EU (67%) and LC (65%).

When AS and IHS were compared per 1 kg of lettuce growth after 52 days (Fig. 8), the smaller differences in CED (21%, AS < IHS) and WD (31%, AS > IHS) were due mainly to the cumulative effect of nutrient and energy use in these intensive systems. Hence, as reported in previous studies (Boxman et al., 2017; Forchino et al., 2017; Xie and Rosentrater, 2015), energy use, mainly for pumping, contributed greatly to environmental impacts, and more broadly operation of the RAS (Cao et al., 2013) in the AS, while use of nutrients from the chemical industry in the IHS contributed the most to CED. For WD, since the French energy mix comes mainly from nuclear energy and hydroelectricity, both of which depend greatly on water, these two energy sources increased impact, especially when heating is required to maintain activity in winter (Love et al., 2015), and much more in AS because it required more water. In contrast, the origin of nutrients used to grow lettuce contributed most to the larger differences in NPPU (100%), GWP100 (73%), AC (70%), EU (52%) and LC (41%). Using formulated feed as a nutrient source caused greater NPPU in the AS than in the IHS, whose use of nutrients from the chemical industry contributed to greater GWP100, AC, EU and LC impacts.

3.5. Limitations

Several limitations of the study must be considered to generalize the results. The study was performed in winter, which could have decreased lettuce and carp growth. Thus, the FCR of carp was increased by water temperature (but remained in the range of FCRs observed in the literature). The study was set to the duration of the lettuce production cycle, which is shorter than that of the carp, thus limiting application of the mass balance, especially to the percentage of P from feed recovered in fish and lettuce biomass, and thus calculation of the AllocLettuce proportion used in the LCA. Thus, increasing the duration of the experiment to a cycle length more suitable for fish development, as Naegel (1977) did, would reduce limitations, especially the effects of season and FCR.

4. Conclusion

Based on mass balance calculations for N and P, it is difficult to determine the advantages of lettuce production in the AS studied in decreasing environmental impacts compared to those of the IHS. The percentages of N (19.3%) and P (20.6%) from feed recovered in fish and lettuce in the AS agreed with those observed for conventional fish aquaculture. Lettuce did remove nutrients from wastewater, but only a small percentage (0.6% N and 0.7% P) of the available nutrients from feed released by the fish. Thus, it is essential to balance the sizes of the fish and crop compartments. According to the LCA, lettuce production had lower impacts in the AS than in the IHS for GWP100, AC, EU and LC; however, the difference in CED was less clear. Using nutrients from formulated feed decreased climate change impacts but increased the use of natural resources (NPPU). To our knowledge, LCA has not been performed for carp reared in an AS or RAS; therefore, it was not possible to compare carp production in this AS to that in other systems. To supplement the assessment, it would be useful to assess relative environmental impacts of producing carp in the AS and in an individual RAS. In addition, the FCR was high, which increased environmental impacts. From the water preservation viewpoint, since N and P increase eutrophication potential, avoiding their release into the environment is a crucial environmental issue. In the future, to generate results that address the objective more completely, it would be useful to increase the crop area to attain the recommended input of fish feed m^{-2} of plant area day^{-1} and to add iron supplements. Thus, in a more optimized system, the AllocLettuce proportion should increase, decreasing environmental impacts of lettuce produced in the AS compared to those in the IHS. Finally, when calculating the mass balance, additional gas emission measurements would be useful to investigate the nature of unaccounted-for N, which is assumed to be due mainly to denitrification, but this has not been measured directly.

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Appendix A

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Table A1
Life Cycle Inventory for the production of 94.4 kg of lettuce in the Aquaponics System on a 52-days cycle. RAS for Recirculating Aquaculture System, HS for Hydroponics System, MBBR for Moving Bed Biofilm Reactor.

Buildings					
	Quantity	Unit	Process	Database	
Greenhouse	11.68	m^2*year	Greenhouse, glass walls and roof, metal tubes/FR/I U	EcoAlim AGBv1.3	
Water consumption					
Use	Quantity	Unit	Process	Database	
Circulating water in RAS	945	kg	Tap water {Europe without Switzerland}| market for | Alloc Rec, U	ecoinvent v3	
Circulating water in HS	2200	kg	Tap water {Europe without Switzerland}| market for | Alloc Rec, U	ecoinvent v3	
Makeup water	2888	kg	Tap water {Europe without Switzerland}| market for | Alloc Rec, U	ecoinvent v3	
Energy consumption					
	Quantity	Unit	Process	Database	
Electricity consumption in RAS	221	kWh	Electricity, low voltage, production FR, at grid/FR U	ecoinvent v3	
Gas consumption in RAS	448	MJ	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atmospheric non-modulating < 100 kW | Alloc Rec, U	ecoinvent v3	
Electricity consumption	1,123	kWh	Electricity, low voltage, production FR, at grid/FR U	ecoinvent v3	
Gas consumption	4,254	MJ	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atmospheric non-modulating < 100 kW | Alloc Rec, U	ecoinvent v3	
Equipment					
	Quantity	Unit	Process	Database	Lifetime (y)
Pipes used in the RAS	0.0484	kg	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Alloc Rec, U	ecoinvent v3	30
Fish tanks	0.0285	kg	Glass fibre reinforced plastic, polyester resin, hand lay-up {RER}| production | Alloc Rec, U	ecoinvent v3	30
Air compressor in RAS	0.0010	p	Air compressor, screw-type compressor, 4 kW {GLO}| market for | Alloc Rec, U	ecoinvent v3	5
Rotary drum filter	0.1383	kg	Metal working machine, unspecified {RER}| production | Alloc Rec, U	ecoinvent v3	7
Settling tank in RAS	0.0202	kg	Glass fibre reinforced plastic, polyester resin, hand lay-up {RER}| production | Alloc Rec, U	ecoinvent v3	30
Tanks used for sediment in RAS	0.0017	kg	Fleece, polyethylene {RER}| production | Alloc Rec, U	ecoinvent v3	30
Pump for sediment in RAS	0.0336	kg	Metal working machine, unspecified {RER}| production | Alloc Rec, U	ecoinvent v3	4
Flocculating agent	0.0295	kg	Polyacrylamide {GLO}| market for | Alloc Rec, U	ecoinvent v3	
Pump to circulate water in RAS	0.0194	kg	Metal working machine, unspecified {RER}| production | Alloc Rec, U	ecoinvent v3	4
MBBF in RAS	0.0315	kg	Fleece, polyethylene {RER}| production | Alloc Rec, U	ecoinvent v3	30
Media of the MBBR	0.3330	kg	Polypropylene, granulate {RER}| production | Alloc Rec, U	ecoinvent v3	10
Common tank	0.0242	kg	Fleece, polyethylene {RER}| production | Alloc Rec, U	ecoinvent v3	30
Potassium carbonate	0.3874	kg	Potassium carbonate {GLO}| market for | Alloc Rec, U	ecoinvent v3	
Commercial carp feed	14.0000	kg			
Pipes used in the HS	0.1183	kg	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Alloc Rec, U	ecoinvent v3	30
Raft beds component	3.7478	kg	Aluminium alloy, metal matrix composite {RoW}| aluminium alloy production, Metallic Matrix Composite | Alloc Rec, U	ecoinvent v3	20
Raft beds component	1.8953	kg	Synthetic rubber {GLO}| market for | Alloc Rec, U	ecoinvent v3	3
Rafts	0.3620	kg	Polystyrene foam slab {GLO}| market for | Alloc Rec, U	ecoinvent v3	4
Pump to circulate water in HS	0.3563	kg	Metal working machine, unspecified {RER}| production | Alloc Rec, U	ecoinvent v3	4

(*continued on next page*)

Table A1 (*continued*)

	Buildings				
		Quantity	Unit	Process	Database
	Commercial carp feed (for 100 kg)				
		Quantity	Unit	Process	Database
	Wheat	34.000	%	Wheat feed flour, animal feed, at plant/FR U	EcoAlim AGBv1.3
	Soybean meal	25.000	%	Soybean meal BR, crushing in France, animal feed, at french mill, average/FR U	EcoAlim AGBv1.3
	Rape meal	17.000	%	Rape meal {GLO}| market for | Alloc Rec, U	EcoAlim AGBv1.3
	Fish meal	10.000	%	Fish meal with waste water treatment, Peru, at feed plant/FR S	EcoAlim AGBv1.3
	Fish oil	6.000	%	Fish oil, with wastewater treatment, from Peru, at feed plant/FR S	EcoAlim AGBv1.3
	Soya concentrate	4.000	%	Soya concentrate, Brazil to french feed plant FR U	personnal data
	Monocalcium phosphate	2.300	%	Monocalcium phosphate, animal feed, at retailer gate/FR U	EcoAlim AGBv1.3
	L-Lysine	0.500	%	L-Lysine HCl, animal feed, at retailer gate/FR U	EcoAlim AGBv1.3
	DL-Methionine	0.100	%	DL-Methionine, animal feed, at retailer gate/RER U	EcoAlim AGBv1.3
	Additif premix	1.100	%	Additif premix, french plant production to french feed plant, FR U	personnal data
	transport	80.000	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	ecoinvent v3
	Electricity	11.970	kWh	Electricity, medium voltage {FR}| market for | Alloc Rec, S	EcoAlim AGBv1.3
	Gas	27.921	kWh	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atmospheric non-modulating < 100 kW | Alloc Rec, U	ecoinvent v3
	Water	25.950	kg	Tap water {Europe without Switzerland}| market for | Alloc Rec, U	ecoinvent v3
	Bags	0.372	kg	Packaging film, LDPE, at plant/RER U	ecoinvent v3
	Transport				
		Quantity	Unit	Process	Database
	Transport of material for RAS	0.50	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	ecoinvent v3
	Transport of material for HS	3.48	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	ecoinvent v3
	Emissions				
		Quantity	Unit	Process	
towards water	Total Nitrogen	0.274	kg	Nitrogen, total	
	Total Phosphorus	0.034	kg	Phosphorus, total	
towards soil	Total Nitrogen	0.066	kg	Nitrogen, total	
	Total Phosphorus	0.056	kg	Phosphorus, total	

Table A2
Life Cycle Inventory for the production of 115.6 kg of lettuce in the Individual Hydroponics System on a 52-days cycle.

	Buildings					
		Quantity	Unit	Process	Database	
	Greenhouse	3.7	m^2*year	Greenhouse, glass walls and roof, metal tubes/FR/I U	EcoAlim AGBv1.3	
	Energy consumption					
		Quantity	Unit	Process	Database	
	Electricity consumption	1,123	kWh	Electricity, low voltage, production FR, at grid/FR U	ecoinvent v3	
	Gas consumption	5,530	MJ	Heat, central or small-scale, natural gas {Europe without Switzerland}| heat production, natural gas, at boiler atmospheric non-modulating < 100 kW | Alloc Rec, U	ecoinvent v3	
	Equipment					
		Quantity	Unit	Process	Database	Lifetime (y)
	Pipes	0.1183	kg	Polyvinylchloride, bulk polymerised {RER}| polyvinylchloride production, bulk polymerisation | Alloc Rec, U	ecoinvent v3	30
	Raft beds component	3.7478	kg	Aluminium alloy, metal matrix composite {RoW}| aluminium alloy production, Metallic Matrix Composite | Alloc Rec, U	ecoinvent v3	20
	Raft beds component	1.8953	kg	Synthetic rubber {GLO}| market for | Alloc Rec, U	ecoinvent v3	3
	Rafts	0.3620	kg	Polystyrene foam slab {GLO}| market for | Alloc Rec, U	ecoinvent v3	4
	Pump to circulate water in HS	0.3563	kg	Metal working machine, unspecified {RER}| production | Alloc Rec, U	ecoinvent v3	4
	Fertilizing solution	3,520.0000	kg			
	Fertilizing solution (for 100 kg)					
		Quantity	Unit	Process	Database	
	Nitric acid	2.0000	kg	Nitric acid, without water, in 50% solution state {GLO}| market for | Alloc Rec, U	ecoinvent v3	
	Ammonium nitrate	4.0000	kg	Ammonium nitrate, as N {GLO}| market for | Alloc Rec, U	ecoinvent v3	
	Monopotassium phosphate	2.0000	kg	Phosphate fertiliser, as P2O5 {RER}| ammonium nitrate phosphate production | Alloc Rec, U	ecoinvent v3	
	Potassium sulfate	5.0000	kg	Potassium nitrate {GLO}| market for | Alloc Rec, U	ecoinvent v3	
	Magnesium sulfate	4.0000	kg	Magnesium sulfate {GLO}| market for | Alloc Rec, U	ecoinvent v3	
	Microelements	0.1428	kg	Chemical, inorganic {GLO}| market for chemicals, inorganic | Alloc Rec, U	ecoinvent v3	
	Iron	0.0480	kg	Chemical, inorganic {GLO}| market for chemicals, inorganic | Alloc Rec, U	ecoinvent v3	
	Water	82.8092	kg	Tap water {Europe without Switzerland}| market for | Alloc Rec, U	ecoinvent v3	
	Transport					
		Quantity	Unit	Process	Database	
	Transport of material for HS	3.48	tkm	Transport, freight, lorry 7.5-16 metric ton, EURO3 {GLO}| market for | Alloc Rec, U	ecoinvent v3	
	Emissions					
		Quantity	Unit	Process		
towards water	Nitrate	1358720	mg	Nitrate		
	Nitrite	143968	mg	Nitrite		
	Ammonium, ion	492.8	mg	Ammonium, ion		
	Phosphate	193600	mg	Phosphate		
	Potassium	187193.6	mg	Potassium		
	Water	3520	kg	Water		
	Iron	10278.4	mg	Iron		

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